



# NO<sub>x</sub> Emissions Characteristics and Correlation Equations of Two P&W's Axially Staged Sector Combustors Developed Under NASA Environmentally Responsible Aviation (ERA) Project

*Zhuohui J. He*  
*Glenn Research Center, Cleveland, Ohio*

## NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA Scientific and Technical Information (STI) Program plays a key part in helping NASA maintain this important role.

The NASA STI Program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI Program provides access to the NASA Technical Report Server—Registered (NTRS Reg) and NASA Technical Report Server—Public (NTRS) thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- **TECHNICAL PUBLICATION.** Reports of completed research or a major significant phase of research that present the results of NASA programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers, but has less stringent limitations on manuscript length and extent of graphic presentations.
- **TECHNICAL MEMORANDUM.** Scientific and technical findings that are preliminary or of specialized interest, e.g., “quick-release” reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.
- **CONTRACTOR REPORT.** Scientific and technical findings by NASA-sponsored contractors and grantees.
- **CONFERENCE PUBLICATION.** Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.
- **SPECIAL PUBLICATION.** Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.
- **TECHNICAL TRANSLATION.** English-language translations of foreign scientific and technical material pertinent to NASA's mission.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at <http://www.sti.nasa.gov>
- E-mail your question to [help@sti.nasa.gov](mailto:help@sti.nasa.gov)
- Fax your question to the NASA STI Information Desk at 757-864-6500
- Telephone the NASA STI Information Desk at 757-864-9658
- Write to:  
NASA STI Program  
Mail Stop 148  
NASA Langley Research Center  
Hampton, VA 23681-2199



# NO<sub>x</sub> Emissions Characteristics and Correlation Equations of Two P&W's Axially Staged Sector Combustors Developed Under NASA Environmentally Responsible Aviation (ERA) Project

*Zhuohui J. He*  
*Glenn Research Center, Cleveland, Ohio*

National Aeronautics and  
Space Administration

Glenn Research Center  
Cleveland, Ohio 44135

## **Acknowledgments**

This study was funded by NASA's Environmentally Responsible Aviation (ERA) project

*Level of Review:* This material has been technically reviewed by technical management.

Available from

NASA STI Program  
Mail Stop 148  
NASA Langley Research Center  
Hampton, VA 23681-2199

National Technical Information Service  
5285 Port Royal Road  
Springfield, VA 22161  
703-605-6000

This report is available in electronic form at <http://www.sti.nasa.gov/> and <http://ntrs.nasa.gov/>

# **NO<sub>x</sub> Emissions Characteristics and Correlation Equations of Two P&W's Axially Staged Sector Combustors Developed Under NASA Environmentally Responsible Aviation (ERA) Project**

Zhuohui J. He

National Aeronautics and Space Administration

Glenn Research Center

Cleveland, Ohio 44135

## **Abstract**

Two P&W's axially staged sector combustors have been developed under NASA Environmentally Responsible Aviation project. One combustor was developed under ERA Phase I, and the other was developed under ERA Phase II. Nitrogen oxides (NO<sub>x</sub>) emissions characteristics and correlation equations for these two sector combustors are reported in this article. The Phase I design was to optimize the NO<sub>x</sub> emissions reduction potential, while the Phase II design was more practical and robust. Multiple injection points and fuel staging strategies are used in the combustor design. Pilot-stage injectors are located on the front dome plate of the combustor, and main-stage injectors are positioned on the top and bottom (Phase I) or on the top only (Phase II) of the combustor liners downstream. Low power configuration uses only pilot-stage injectors. Main-stage injectors are added to high power configuration to help distribute fuel more evenly and achieve lean burn throughout the combustor yielding very low NO<sub>x</sub> emissions. The ICAO landing-takeoff NO<sub>x</sub> emissions are verified to be 88 percent (Phase I) and 76 percent (Phase II) under the ICAO CAEP/6 standard, exceeding the ERA project goal of 75 percent reduction, and the combustors proved to have stable combustion with room to maneuver on fuel flow splits for operability.

## **Introduction**

Aircraft nitrogen oxides (NO<sub>x</sub>) emissions can cause problems to the atmosphere, such as smog and ozone in the lower troposphere and decreased ozone in the stratosphere (Wey and Maurice 2003). Over the past two decades, NO<sub>x</sub> emissions reduction has been a major focus for NASA in aeronautical science research. During the 1990s, NASA's High-Speed-Research (HSR) program focused on developing combustor concepts that reduce NO<sub>x</sub> emissions for supersonic aircrafts. In the 2000s, NASA's Ultra-Efficient-Engine-Technology (UEET) program, Fundamental Aeronautics program, and Advanced Subsonic Technology program found reductions in NO<sub>x</sub> emissions for subsonic aircraft emission. Currently, NASA's Environmentally Responsible Aviation (ERA) project aims to reduce the subsonic aircraft engine NO<sub>x</sub> emissions by 75 percent with respect to ICAO CAEP/6 level (Chang, et al. 2013). To achieve this goal, NASA is collaborating with fuel injector companies (Woodward, Parker, Goodrich) and engine companies (GE and P&W) to develop state of the art low-NO<sub>x</sub> combustion technologies. Under an ERA project contract, Pratt & Whitney (P&W) developed an axially staged combustor concept, called Axially Controlled Stoichiometry (ACS) combustor, to reduce NO<sub>x</sub> emissions.

Combustion concept designs for commercial aircraft fall into two categories: rich-front-end and lean-front-end. As shown in Figure 1, NO<sub>x</sub> emissions are sensitive to flame temperatures. The flame temperature reaches the maximum at equivalence ratio around one. As equivalence ratio departs from stoichiometric, the flame temperature decreases. Rich-Burn Quick-Mixing Lean-Burn (RQL) combustors utilize a rich-front-end designed to reduce NO<sub>x</sub> emissions. In this concept, the combustor front end or primary zone burns fuel rich. In order to minimize NO<sub>x</sub> emissions and complete combustion, this fuel rich

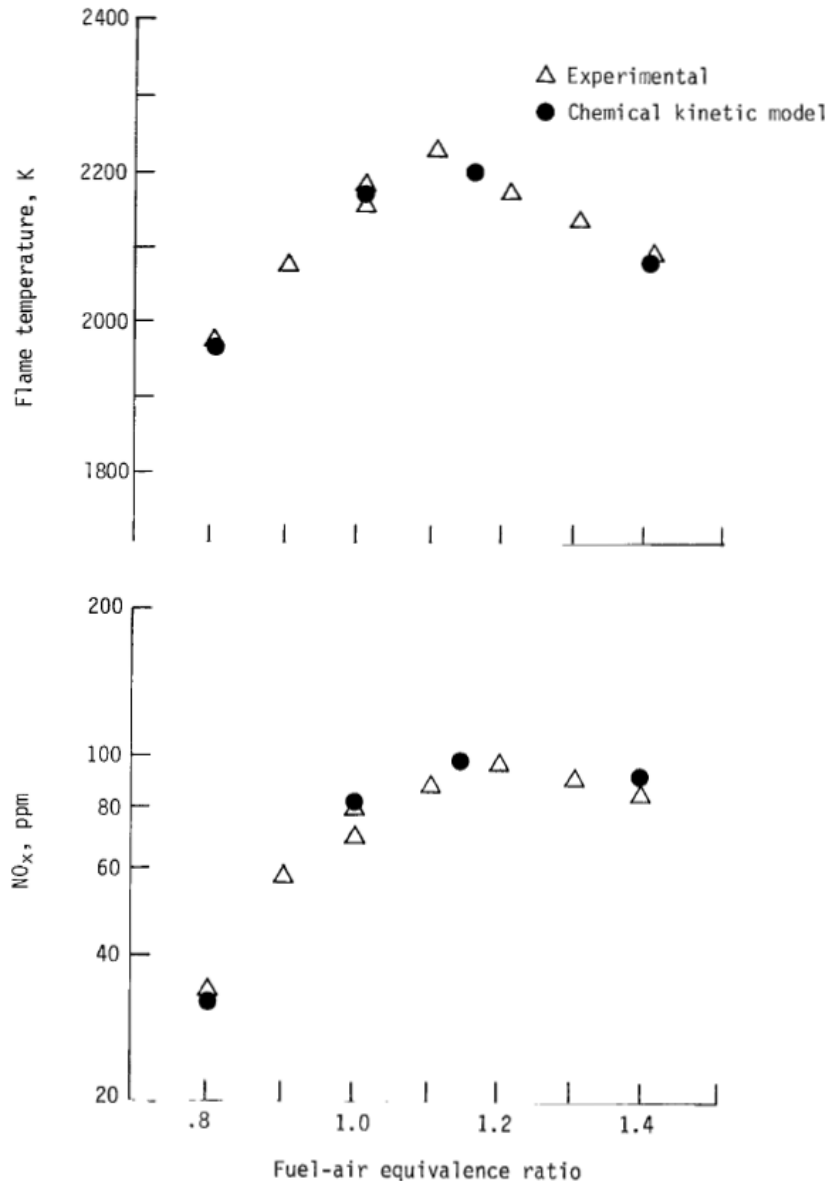


Figure 1.—Experimental and calculated results for JP-4-air mixtures with combustor inlet temperature of 455 K (Jachimowski and Wilson, 1980).

combustion mixture is diluted to lean with the quench air jets, minimizing residence time near stoichiometric conditions. A rich primary combustion zone provides a stable flame and a large combustion operability range. Thus, rich-front-end combustors are commonly used in combustor designs.

Lean-front-end combustors operate fuel lean throughout the combustor. Most of the combustion air enters through the combustor dome and through fuel injectors or mixing chambers. A minimal amount of air is allocated for cooling. These concepts vary from single fuel injector concepts to multiple fuel injectors in each sector of the combustor. In all concepts, however, the fuel entering the combustor is well mixed with incoming process air and is fuel lean. Lean-front-end concepts require good fuel air mixing to limit local hot spots that generate NO<sub>x</sub>.

Aircraft engines operate in a wide range power conditions (wide range of pressures, temperatures, and flows). A single fuel injector may not be able to atomize the fuel sufficiently for good fuel-air mixing. As a result, lean-front-end concepts usually involve multiple fuel injection points. In low power conditions, only parts of the fuel injectors are used. This gives local fuel air ratios that are sufficiently high to create continuous stable combustion. In higher power conditions, all fuel injectors are used to distribute fuel more evenly throughout the combustor so no region has high enough fuel air ratios to produce high  $\text{NO}_x$ . The design of the fuel injector system is critical to creating a fuel-lean combustor that is both stable at low power and produces low  $\text{NO}_x$  emissions at high power.

New aircraft combustor concept screening often starts in a flame-tube test facility, where a fuel injector and accompanying fuel injector cup is tested at various aircraft operational conditions. An example of flame tube test facility is the CE-5 test facility at NASA Glenn Research Center (Bianco 1995). The fuel-air mixture is injected into a flame tube with a cast ceramic housing. A gas collection probe is placed downstream of the injector at a distance specified to ascertain the fuel injector/ cup configuration's emissions output.

Once a fuel injector/ cup configuration obtains good stability with low  $\text{NO}_x$ , a sector combustor test, where three to five fuel injector cups of an aircraft annular combustor is utilized to determine the combustor/ fuel injector module's stability and emissions. In this step, effects of combustor liners and interaction between injector cups are assessed.

In this article,  $\text{NO}_x$  emission characteristics and correlation equations of two three-cups P&W ACS sector combustors that developed under ERA program Phase I and Phase II are reported. The sector combustors were tested in NASA Glenn Research Center's Advanced Subsonic Combustion Rig (ASCR). ASCR is capable of testing combustor hardware at high-pressure conditions up to 60 atm. The main goals of this test are to screen the  $\text{NO}_x$  emissions of this combustion concept at four different ICAO LTO power conditions—taxiing (7 percent), approach (30 percent), climbing (85 percent), takeoff (100 percent)—and to develop  $\text{NO}_x$  emissions correlation equations to use for aircraft engine system level analysis.

## **Experimental Facilities and Hardware**

### **Experimental Facilities**

The sector combustor test was conducted at the NASA Glenn Advanced Subsonic Combustion Rig (ASCR). A drawing and a picture of the test rig are shown in Figure 2. This test rig can supply nonvitiated air preheated to 975 K at pressure up to 6200 kPa. The maximum condition vary with air mass flow rate. A venturi meter is used to measure the airflow rate, and turbine meters are used to measure the fuel flow rates. The sector combustor is mounted in a stainless-steel pipe with an 889 mm inside diameter. The combustor section is followed by a water-quench section and backpressure valve. The test rig has four fuel circuits and is capable of on-the-fly mixing JP-8 and alternative aviation fuel at various ratios. The combusted gas samples were collected according to SAE-ARP1256 (SAE international 2011) and analyzed according to the standard gas-analysis procedure, SAE-ARP1533 (SAE International 2004).  $\text{CO}$ ,  $\text{CO}_2$ ,  $\text{O}_2$ ,  $\text{NO}_x$ , and unburned hydrocarbons (UHC) are measured. The combustion rig has diagnostic windows along the combustor section, which could be used for laser diagnostics, or visual fuel leak detection. Dynamic pressures are measured upstream ( $P_3$ ) and inside ( $P_4$ ) the combustor.

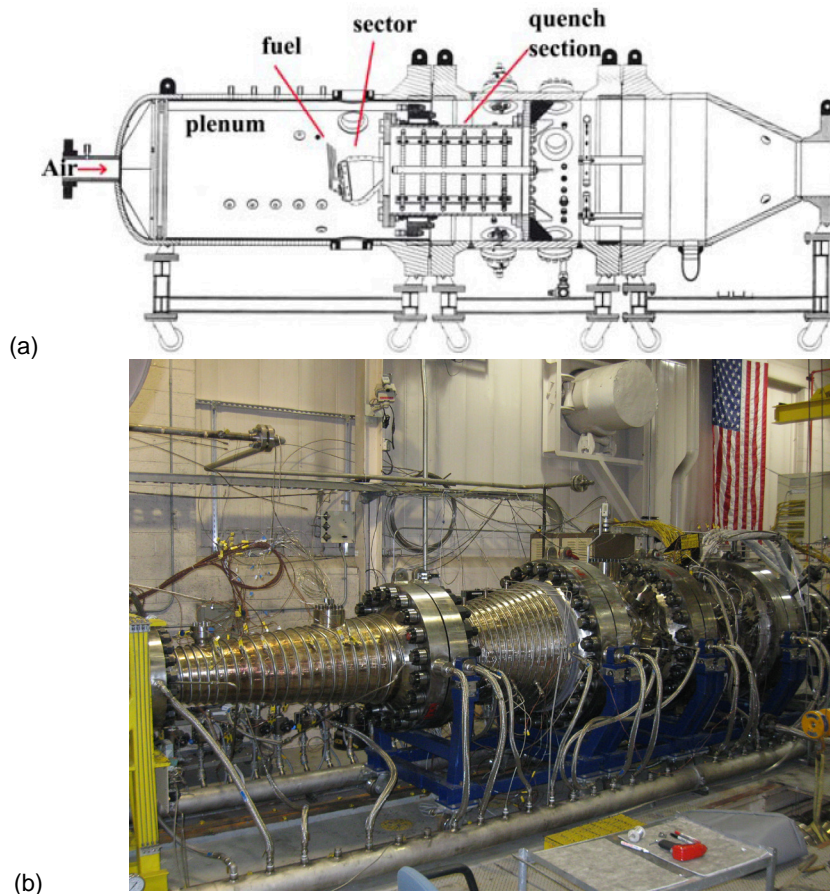


Figure 2.—(a) Drawing and (b) picture of ASCR test facility in NASA Glenn Research Center.

### Sector Combustor Hardware

Two ACS sector combustors were developed by P&W under the NASA ERA project: one combustor was developed under ERA Phase I, while another was developed under ERA Phase II. The Phase I design was to optimize the  $\text{NO}_x$  emissions reduction potential, while the Phase II design was more practical and robust. These two sector combustors were three-cup sectors. Basic drawings for each injector cups are shown in Figure 3. Fuel injection splits into two stages: pilot and main. For Phase I combustor design (Figure 3(a)), pilot-stage injectors are located on the front dome plate of the combustor, and main-stage injectors are positioned on the top and bottom of the combustor liners downstream. For Phase II (Figure 3(b)), the main-stage injectors are positioned on the top of the combustor liners downstream only.

Fuel injection configurations were similar for both ACS sector combustors. Low power configuration only uses pilot-stage injectors, while high power configuration utilizes both pilot-stage and main-stage fuel injectors. As discussed previously, this allows for stable and efficient combustion with low  $\text{NO}_x$  emissions through the entire aircraft operability envelope. To account handle the staging, three fuel circuits are used in this test. One fuel circuit supplies fuel to the main fuel injectors. Two fuel circuits serve the pilot stages injectors.

In order to determine if the configuration obtains efficient burning and low  $\text{NO}_x$  emissions, nine piccolo probes are placed at the exit of the combustor to collect combustion products for gas analysis. The probes were water cooled in order to protect the hardware and quench any additional CO oxidation.



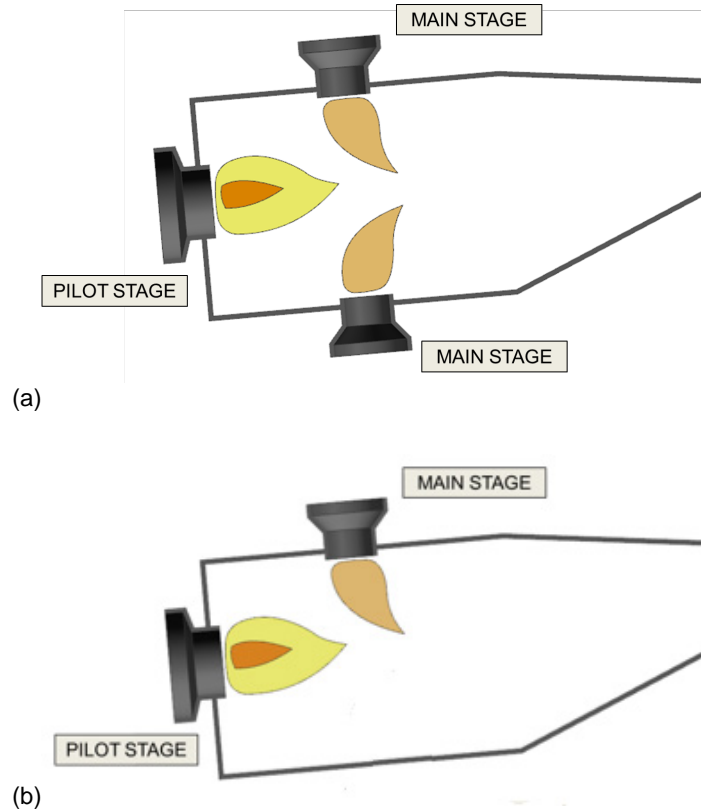


Figure 3.—NASA ERA P&W ASC combustor cross-section view  
(a) Phase I configuration, (b) Phase II configuration.

## Results and Discussion

### Low Engine Power Configuration

For low power engine operational conditions, the overall equivalence ratios are low, and only the pilot-stage injectors are used for fuel injection. Pilot-stage injectors inject fuel through the front dome plate of the combustor. The combustor front-end or pilot zone is designed to have relatively high local fuel air ratio at some locations. This provides a stable pilot combustion zone to prevent lean blow out, combustion instabilities, and to assure efficient combustion. A nominal amount of air enters the combustor through the fuel nozzle cup in order to obtain sufficient stoichiometry to allow for a stable pilot zone. Additional process air enters through the main fuel injector cups, but no fuel is supplied to the main fuel injectors for low power. The remaining air is used for liner cooling.

The combustor temperature profile for the low power configuration is similar to a rich-front-end combustor as shown in Figure 4. The flame temperature is low near the dome. As the fuel-rich combusted gas moves forward, the flame temperature increases then decreases quickly as the fuel-rich combusted gas dilutes with air from the main air swirlers and the front-end liners. The  $\text{NO}_x$  emissions at the combustor front-end and back-end are low due to low flame temperature that greatly reduces thermal  $\text{NO}_x$ . In addition, oxygen depletion at the combustor front-end would reduce the  $\text{NO}_x$  production in that zone (Lefebvre 1998). The hot zone in between the front-end and back-end only occupies small portion of the combustor making the residence time in that zone very low. The middle zone, however, may create the most  $\text{NO}_x$  emissions because it has sufficient temperature and oxygen to do so. The time spent in the

middle zone between front-end and back-end, therefore largely dictates the overall  $\text{NO}_x$  emission during low power operation.

As shown in Figure 5, the  $\text{EINO}_x$  values for low power configuration increase and then decrease before and after overall fuel air equivalence ratio around 0.14 for the Phase I sector combustor and around 0.26 for the Phase II sector combustor. This indicates the middle zone has the most flame locations whose stoichiometry is near stoichiometric at these overall fuel air equivalence ratios. Stoichiometric pilot fuel air equivalence ratio occurs in Phase II sector at higher overall fuel air equivalence ratios than Phase I ( $\Phi = 0.26$  vs. 0.14). More combustion air might inject into the primary combustion zone (combustor front end before the main injectors) in the Phase II sector combustor than Phase I, which might give better fuel air mixing and minimize the size of the local hot zone area. As a result, the Phase II design has lower  $\text{NO}_x$  emissions than the Phase I design.

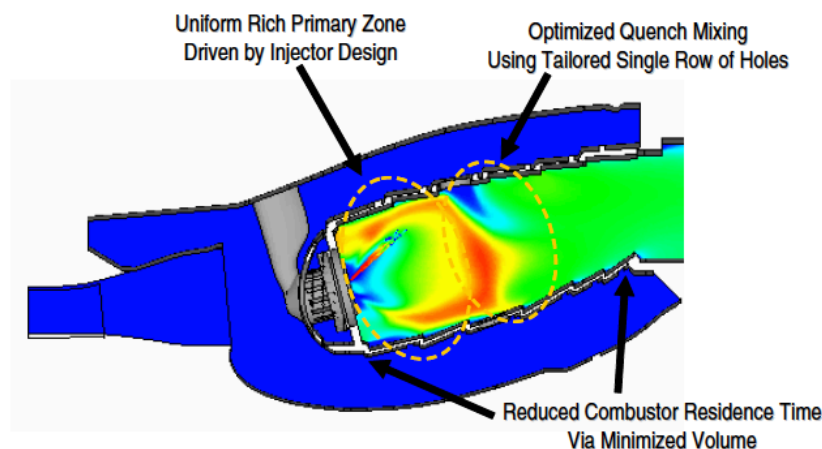


Figure 4.—Temperature profile for the P&W TALON RQL combustor (McKinney, et al. 2007).

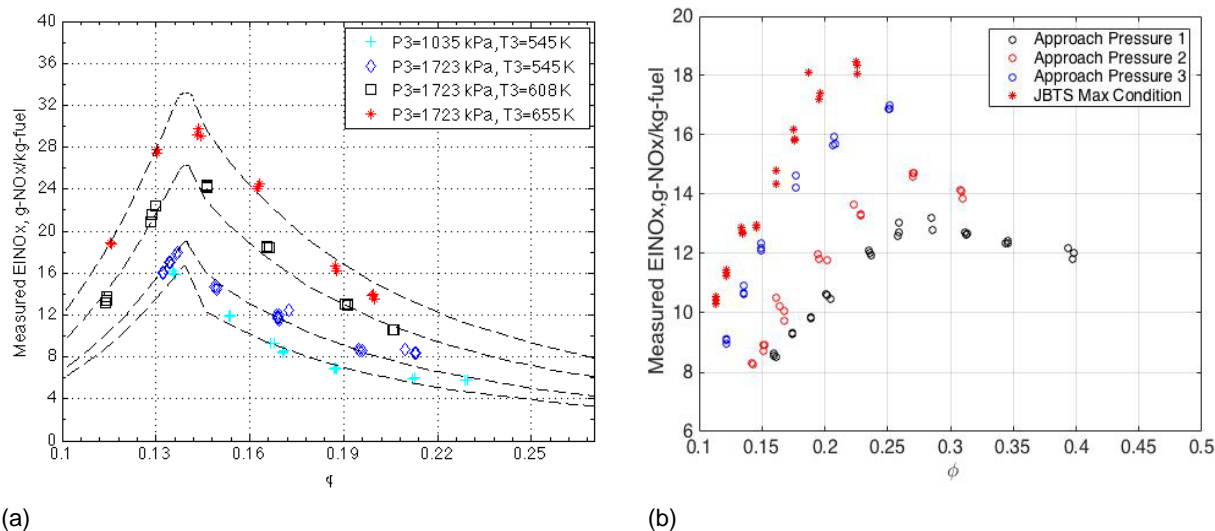


Figure 5.—Low engine power configuration,  $\text{EINO}_x$  versus  $\Phi$ , (a) Phase I design, (b) Phase II design.

## High Engine Power Configuration

For higher power configuration, both pilot-stage and main-stage injectors are fueled. Main-stage injectors are located axially downstream of the pilot-stage injectors on OD (Phase I and Phase II) and ID (Phase I only) of the combustor. There are several advantages of this combustor design. First, with more fuel injection points, fuel and air are able to mix more evenly throughout the combustor and achieve overall lean burn without any pockets of unmixedness (which can lead to high temperatures and high  $\text{NO}_x$  emissions). Second, the main-stage injectors are positioned downstream of the pilot injectors. Airflow through main-stage injectors does not affect the swirl-stabilized pilot zone, which is important for combustion flame stabilities (Pratt & Whitney 2012). Third, higher upstream temperature makes the main-stage fuel burn efficiently, even with a low residence time. The ability to burn efficiently with a low residence time assures low CO, UHC, and  $\text{NO}_x$  emissions. This is of particular importance because most of the fuel injected at high power conditions comes from the main stage. Advanced Low  $\text{NO}_x$  Combustor Technology-

High power configuration emission characteristics are similar to many lean burn concepts that tested previously at NASA Glenn Research Center. Figure 6(a) shows the Phase I sector combustion  $\text{NO}_x$  emissions as a function of overall equivalence ratio (local pilot  $\Phi$  stays at 0.6) for Phase I design. The influence of inlet air temperature and pressure are similar to the low power configuration, with  $P_3^{0.374}$  and  $e^{T_3/175}$ .  $\text{EINO}_x$  emissions are a power function of fuel air equivalence ratio, with  $\Phi^{4.62}$ . The high  $\Phi$  dependence for lean combustion has been observed before in a NASA 9-points LDI concept with  $45^\circ$  air swirlers ( $\Phi^{5.07}$ ). That study showed that the swirl angle had a determining factor on the influence coefficient for  $\Phi$ . CFD studies suggested a  $45^\circ$  swirler does not allow for a strong central recirculation zone, but a flow field with increased swirl angle (which showed a lower dependence on  $\Phi$ ) did have a strong central recirculation zone. (Kumud, Mongia and Lee 2013). The surface area of the flame that is outer recirculation zone stabilized may be greater than an inner circulation zone stabilized flame, and this could lead to higher influence of  $\Phi$ .

For Phase II design, main injectors located only axially downstream on the top liner. As comparing the data shown on Figure 6(a) and (b), the Phase II high power configuration has higher  $\text{NO}_x$  emissions than Phase I. In addition, the rate of change in  $\text{NO}_x$  emissions changes and increases as the over fuel air equivalence ratio pass around 0.35. The change is unknown, and it might due the increase in thermo  $\text{NO}_x$  emissions at high flame temperatures (Lefebvre 1998). Also, observing from the Phase II data,  $\text{NO}_x$

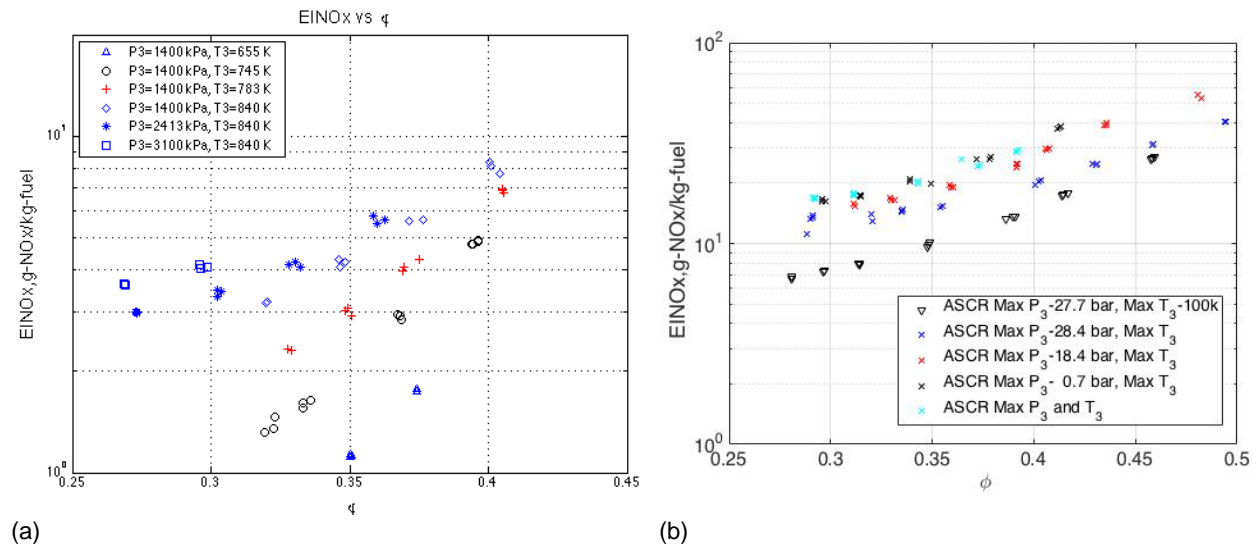


Figure 6.—high power configuration  $EINO_x$  versus  $\Phi$ , (a) Phase I design, (b) Phase II design. emissions become less dependent on inlet air pressure at let air pressure of 3800 kPa or above. Overall, the high power configurations have lower  $NO_x$  emissions than the low power configurations. For Phase I design, the  $EINO_x$  emissions value at  $P_3 = 2000$  kPa,  $T_3 = 655$  K, and  $\Phi = 0.3$  is about 7 for low power configuration, while high power configuration  $EINO_x$  emissions value is about 1. This may be because there is little or no pockets of near stoichiometric burner for this the well mixed mains (which is where most of the fuel is being added).

### **$EINO_x$ Correlation Equations**

The  $EINO_x$  emissions correlation equations listed in Table 1 for Phase I design and Table 2 for Phase II design. For the high power configuration, the local pilot zone equivalence ratio stays at 0.6.  $EINO_x$  emissions are a function of inlet air pressure ( $P_3$ ), inlet air temperature ( $T_3$ ), and equivalence ratio ( $\Phi$ ). The method used in developing these equations is described in a previous study on Parker Hnnifin’s multipoint LDI injector (He, Chang and Follen 2014).  $EINO_x$  dependency on  $P_3$  is small, which ranges from  $P_3^{0.25}$  to  $P_3^{0.50}$ , and it is an exponential function of  $T_3/175$ . The greatest change is on the fuel air equivalence ratio dependence, which ranges from  $\Phi^{-2.15}$  to  $\Phi^{4.62}$ . The ability to collapse all of the high power data into a single equation may be due to the fact that the pilot equivalence ratio remained constant. This may indicate that the pilot zone has the largest impact of emissions. A pilot  $\Phi$  of 0.5 was also tested, but not included in the correlation because it was judged as less superior than the  $\Phi = 0.6$  case for overall operability. Data from the  $\Phi = 0.5$  case is presented in the next section of this paper. For Phase I low power configuration, influence of fuel air equivalence ratio on the  $NO_x$  emissions before and after overall  $\Phi$  of 0.14 are respectively about  $\Phi^{3.2}$  and  $\Phi^{-2.15}$ . An influence coefficient greater than zero indicated an increase in overall  $\Phi$  would increase  $NO_x$  emissions, and an influence coefficient of less than zero indicates an increase in overall  $\Phi$  would tend to decrease the  $NO_x$  emissions. To reduce number of the equations, polynomial terms were used in the Phase II  $EINO_x$  correlation equations due to the changes in slopes between  $EINO_x$  and inlet air pressure, and  $EINO_x$  and fuel air equivalence ratio.

TABLE 1.— $EINO_x$  EMISSIONS CORRELATION EQUATIONS FOR PHASE I

Engine Power Conditions	$NO_x$ Correlation equations
1) Low power configuration ( $\Phi < 0.14$ )	$EINO_x = 76.45 * P_3^{0.25} * e^{\frac{T_3}{175}} * \Phi^{3.2}$
2) Low power configuration ( $\Phi > 0.14$ )	$EINO_x = 0.000237 * P_3^{0.50} * e^{\frac{T_3}{175}} * \Phi^{-2.15}$
3) High power configuration ( $\Phi > 0.30$ )	$EINO_x = 0.36 * P_3^{0.374} * e^{\frac{T_3}{175}} * \Phi^{4.62}$

TABLE 2.— $EINO_x$  EMISSIONS CORRELATION EQUATIONS FOR PHASE II

Low power (for $\phi < 0.3$ , $T_3 < 650$ K, and $P_3 < 1400$ kPa)
$EINO_x = 0.0127 \times e^{\left(\frac{T_3}{195}\right)} \times P_3^{0.48} \times \left(-4.00 + \frac{-2.17}{\phi} + \frac{0.0623}{\phi^2} + \frac{6.324}{\sqrt{\phi}}\right)$
High power (for $\phi < 0.3$ , $T_3 < 650$ K, and $P_3 < 1400$ kPa)
$EINO_x = 0.67 \times e^{\left(\frac{T_3}{171}\right)} \times \left(2.55 + \frac{-3832}{P_3} + \frac{87}{\sqrt{P_3}}\right) \times \left(3.773 + \frac{1.88}{\phi} + \frac{-0.0763}{\phi^2} + \frac{-6.014}{\sqrt{\phi}}\right)$

TABLE 3.—ICAO LANDING-TAKEOFF (LTO) EINO<sub>x</sub> EMISSIONS (WITHOUT HUMIDITY CORRECTIONS)

ICAO engine power conditions, %	Phase I Pilot local $\Phi = 0.5$	Phase I Pilot local $\Phi = 0.6$	Phase II
7	6.16	6.16	1.6
30	6.81	6.81	12.2
85	4.58	9.12	16.4
100	7.45	14.52	25.9
Reduction relative to CAEP/6, %	88	83	76.1

### ICAO Landing-Takeoff (LTO) EINO<sub>x</sub> Emissions

NO<sub>x</sub> emissions at four ICAO LTO power conditions for the two ACS sector combustors were assessed at the NASA Glenn Research Center's ASCR rig, and the resulted EINO<sub>x</sub> values (dry air without humidity corrections) are listed in Table 3. For the 7 and 30 percent engine power conditions, NO<sub>x</sub> emissions are obtained with the low power configurations, and the EINO<sub>x</sub> values are 6.16 and 6.81, respectively, for Phase I design and 1.6 and 12.2 for Phase II design.

The high power configuration was used to assess 85 and 100 percent engine power NO<sub>x</sub> emissions. Two different fuel staging are tested for the Phase I design, one with local pilot zone  $\Phi$  stays at 0.5 and another with local pilot zone  $\Phi$  stays at 0.6. NO<sub>x</sub> emissions for the Phase I design at 85 and 100 percent engine power conditions were experimentally assessed in ASCR with high power configuration (local pilot zone  $\Phi = 0.5$ ). The EINO<sub>x</sub> values are 4.58 and 7.45. Along with the 7 and 30 percent engine power NO<sub>x</sub> emissions, the overall landing-takeoff cycle NO<sub>x</sub> emissions are about 12 percent relative to ICAO CAEP/6 level. As discussed previously in this paper, although a pilot  $\Phi = 0.5$  gives good emissions and operability, there may be less margin than desired over the entire operating envelope. For high power configuration (local pilot zone  $\Phi = 0.6$ ), highest inlet air pressure and temperature tested in ASCR are 3100 kPa and 810 K, respectively. Further testing was limited due to a potential fuel leak in the sector combustor hardware. Using the high power configuration correlation equation, the 85 and 100 percent engine power NO<sub>x</sub> emissions (local pilot zone  $\Phi = 0.6$ ) are estimated as 9.12 and 14.52. The percentage reduction relative to ICAO CAEP/6 is 83 percent. This is significant because this large reduction comes with a design that was found to be stable and flexible with fuel splits, which improved overall operability. The Phase II design is more robust and practical for real engine operations. The resulted LTO NO<sub>x</sub> emissions are higher than the Phase I results, which is about 76.1 percent reduction relative to ICAO CAEP/6 level.

### Summary

The EINO<sub>x</sub> correlation equations and NO<sub>x</sub> emissions results of two P&W Axially Controlled Stoichiometry (ACS) sector combustors are presented in this article. NO<sub>x</sub> emissions for this combustor concept were assessed experimentally at NASA Glenn Research Center's Advance Subsonic combustion Rig over the entire operating range of the LTO cycle. Multiple injection points and fuel staging strategies are used in this combustor design. The low power configuration uses only pilot-stage injectors. Main-stage injectors are added to high power configuration to help distribute fuel more evenly and achieve overall lean burn yielding very low NO<sub>x</sub> emissions. With this advantage, high power configuration NO<sub>x</sub> emissions index are lower than for the low power configuration. This ACS combustor design meets the ERA program goal in reducing NO<sub>x</sub> emissions while maintaining high combustion efficiency and flame stability. The ICAO landing-takeoff NO<sub>x</sub> emissions are verified to be 88 percent (Phase I) and 76 percent (Phase II) under the ICAO CAEP/6 standard, exceeding the ERA project goal of 75 percent reduction, and the combustor proved to have stable combustion with room to maneuver on fuel flow splits for operability.





